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Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: Aug 1, 2015 to Oct 31, 2015

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14. ABSTRACT
This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area ???Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft. The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

Activities this period

During the period of this report, fully coupled simulations of the helicopter hovering near ground at different altitudes have been performed. Time-averaged CFD predictions have been compared with recently published experimental data (Ref. 1). In addition, time-history results for the dynamic response of the helicopter are presented for all the cases. Fully coupled simulations are shown to be feasible, to exhibit reasonable physical behavior, and to capture expected aerodynamic coupling effects. Extended results to a variety of cases, including the presence of walls, and sloped and partial ground effects will be presented in the next quarterly progress report. We will also look at low speed flight conditions near the ground plane to observe the effects of a ground vortex on the helicopter dynamics and control compensation. In addition, implementation of the new coupling interface, using MPMD MPI framework, optimized for faster simulation process has been accomplished.

Rotorcraft/Terrain Interactions

Rotorcraft regularly operates close to the terrain and near large physical objects. This can include flat and sloped terrain, buildings, urban canyons, ships and landing platforms. Helicopter rotor systems generate significant flow velocities that interact with the terrain and with the helicopter airframe itself.

Indeed, appropriate modeling of the rotor inflow (the flow induced in the plane of the rotor that affects the rotor blade airloads) is a critical aspect of rotorcraft modeling and simulation. Well known methods with various levels of fidelity are regularly used in rotorcraft modeling and simulation, such as free wake modeling and finite-state inflow methods. Rotorcraft simulations must also capture the interaction of the main rotor downwash on the airframe. This would include downwash forces on the fuselage and empennage, but might also include more complex interactions that are a function of many variables. Such aerodynamic interactions are typically modeled with empirical look up tables, examples of which can be found in Ref. 2. Basic methods for capturing ground effect are also commonly used; these typically involve a modification of the average induced inflow at the main rotor in order capture the reduced power and collective pitch required when hovering in the In-Ground-Effect (IGE) “cushion”, as summarized in Ref. 3. Free wake solutions can also account for ground effect (Ref. 4) and other vortex methods have also been used (Ref. 5). Extensions to finite-state inflow have been developed to account for ground effect, including partial ground effect and sloped surfaces (Ref. 6). Interactions with more complex objects, such as Navy ships has been investigated using a variety of methods involving CFD, vortex wake modeling, and finite state inflow models (Ref. 7-9).

Both the performance and the handling qualities of a rotorcraft can be highly influenced by the presence of a ground surface or obstructions in close proximity. These interactions can appear in a variety of forms, as positive or negative changes in performance, and as steady and unsteady disturbances on the airframe. Landing on a ship flight deck is a prime example, as it requires flying over partial ship flight deck, flying very close to the ship hangar wall, and operating over a moving flight deck. During such operations, the aircraft will experience a variety of aerodynamic interactions with the surrounding “terrain” (in this case a ship). Figure 1 shows the effect of hovering near both in and out of ground effect (Ref. 9) and the recirculation of the wake when a helicopter hovers near a vertical wall. Both recirculation and ground effect can occur in ship operations, and the degree to which each effect is present depends on the position of the rotor relative the ship superstructure, the area of the hangar face and the relative angle of the ship deck surface, as well as the area of the ship flight deck (Ref 10).

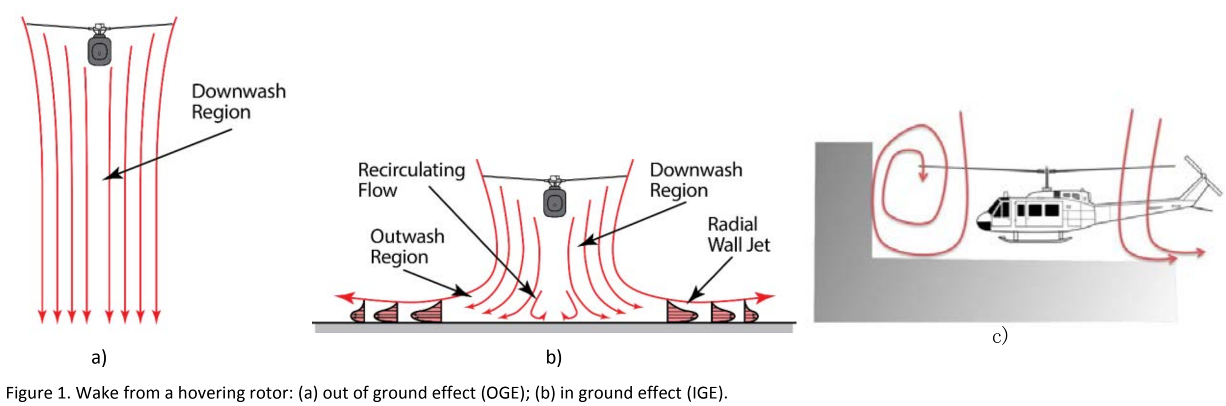


Figure 1. Wake from a helicopter rotor: a) out of ground effect (OGE), b) in ground effect (IGE) (Ref. 1), c) recirculation near wall.

While efficient free-wake methods and finite-state inflow methods have been shown to capture a variety of rotorcraft-terrain interactions, Navier-Stokes CFD offers the most general solution to model complex geometries and while including viscous effects. However, the use of CFD comes with higher computational cost. The objective of this study is the investigation of the influence of aerodynamic

interactions between rotor downwash and terrain on rotorcraft flight dynamics using efficient / low-cost Navier-Stokes flow solutions. An analysis tool is developed using CFD coupled with a helicopter flight simulation model, while avoiding moving grids and other expensive CFD methods. In the coupled simulations, the flight dynamics model is free move within a computational domain, where the main rotor forces are translated into source terms in the Navier-Stokes momentum equations. Simultaneously, the CFD calculates induced velocities that are fed back to the simulation and affect the aero loads in the flight dynamics. The CFD solver models the inflow, ground effect, and interactional aerodynamics in the flight dynamics simulation. The tool was developed in previous research with the main goal of investigating interaction of rotorcraft and ship airwakes in sea-based operations (Ref. 11). This study extends the analysis to more general operations, such as operation in ground effect and near walls.

Simulation Results

Simulation results were performed using fully coupled solutions of the rotorcraft flight dynamics and CFD flow field. All calculations were performed using parallel computing with 128 CPUs on the COCOA4 cluster at Penn State. Some of the outwash flow results have been compared with the recently published experimental data. At present we have not found suitable flight data to compare with the simulations.

<u>Hover IGE</u>

As an initial case, fully coupled flight dynamics and CFD simulations of a helicopter hovering in an open domain in ground effect have been performed for three different altitudes above ground. For all three cases, same computational domain and flight dynamics model have been used. Unsteady simulations were performed for 30 seconds. The fully coupled simulations start in freeze-mode, in which the helicopter body is held at a specific position in the air and the rotor blades move freely. At the beginning of the simulation, GENHEL-PSU uses a Pitt-Peters finite state inflow model to trim and sends the blade positions and aero loads to the flow solver as initial values. After initialization, GENHEL-PSU starts to use the CFD-predicted induced velocities to calculate the blade loads, but the helicopter stays in freeze mode. This buffer phase helps the CFD solver to develop the rotor downwash and prevents potential CFD convergence problems. After the 5th second of the simulation, GENHEL- PSU enters free fly-mode. In this mode, both the helicopter and the rotor disk move freely while GENHEL-PSU and the CRUNCH CFD® solver is fully coupled to each other. The controller helps to regulate the aircraft and it reaches a new hover trim condition.

The CFD results have been compared with the available experimental data from a recent work (Ref. 1). Figure 2 shows the comparison of non-dimensional outwash velocity profiles obtained from CFD and experimental data at z/R=1.0, $\psi = 270°$, $C_T = 0.006$ and radial stations indicated. It should be noted that the experimental data is measured at z/R=1.14 and a single main rotor airframe with 6 ft. radius rotor blades was used in the tests, however CFD simulations performed with an isolated rotor with a radius of 26.5 ft. Figure 2 shows that for a rotor height of z/R=1.0, the peak outwash velocity occurring between 1.5-1.6 r/R. At the same height, the experimental results show $1.8V_h$ maximum outwash velocity. However, the maximum outwash velocity observed in CFD predictions is $1.6V_h$. This difference could be caused by the numerical dissipation originated from the decreasing grid resolution at this region.

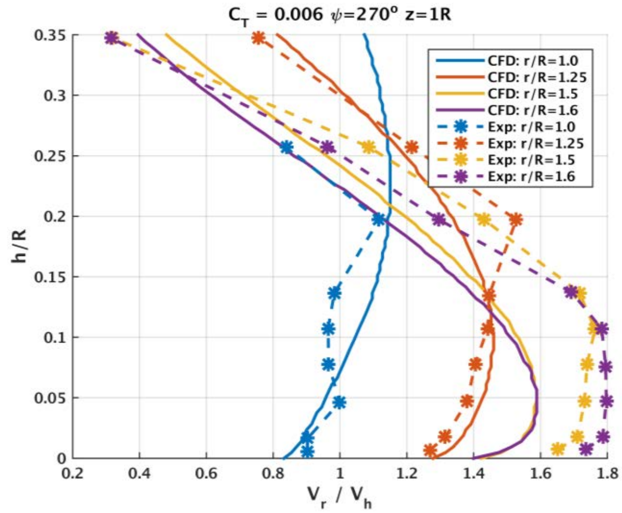


Figure 2. Non-dimensionalized outwash velocity profiles obtained from CFD and experimental data at z/R=1.0, ψ = 270° and C_T = 0.006 and radial stations indicated.

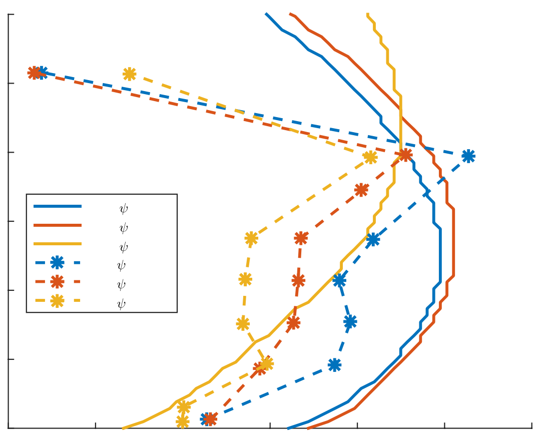


Figure 3. Mean non-dimensionalized outwash velocity profiles for the model at C_T = 0.006, r/R = 1.0 and z/R= 1.0 at different azimuth locations.

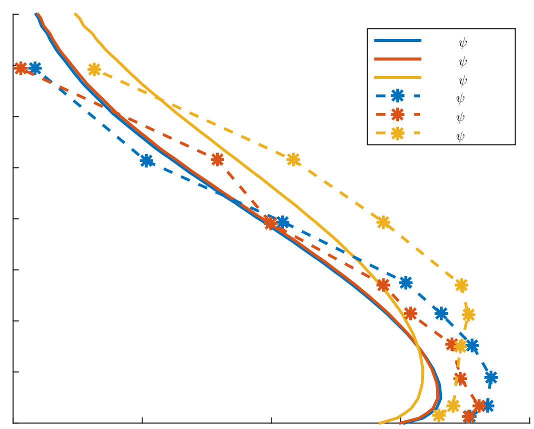


Figure 4. Mean non-dimensionalized outwash velocity profiles for the model at C_T = 0.006, r/R = 1.5 and z/R = 1.0 at different azimuth locations.

Figure 3 and Figure 4 show the comparison of mean non-dimensionalized outwash velocity profiles obtained from CFD and experimental at z/R=1.0, CT = 0.006 and different azimuth locations indicated for two different radial stations, r/R =1.0 and r/R=1.5 respectively. The experimental results show that the mean outwash velocity varies with respect to the measurement azimuth. For an ideal hover with no tip-path plane, zero-hub moment and no interactions with airframe, it would be expected that the outwash flow field to be perfectly axisymmetric. The azimuthal dependency on experimental results was explained by Tanner (Ref. 9) as a result of airframe/rotor downwash interaction. In our case, the CFD has been performed with an isolated rotor and it can be seen on the Figure 3 and Figure 4 that the outwash velocities are essentially identical at 0 and 180 azimuth degrees. There is some difference in CFD outwash at 270° azimuthal location. This is a result of the helicopter trim is such that the tip path

plane is not perfectly parallel to the ground plane and the TPP is slightly tilted left side down such that the main rotor thrust is towards the left and counteracting the tail rotor thrust to the right. However, the general trends in the numerical results are acceptable for the current phase of this research.

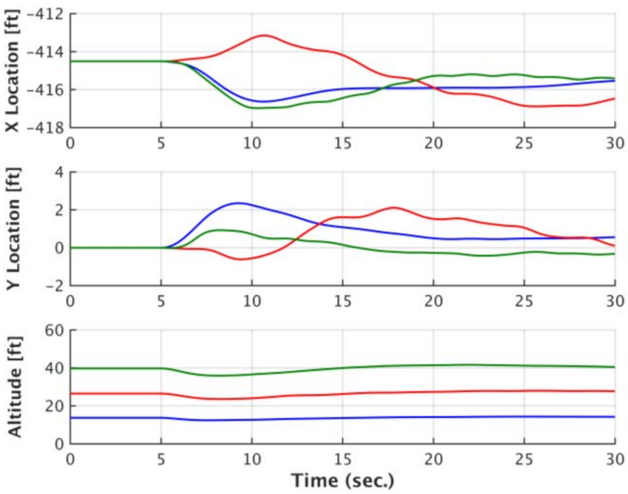


Figure 5. Variations in positions of the simulated helicopter hovering IGE, at z=0.5R, z=1R and z=1.5R

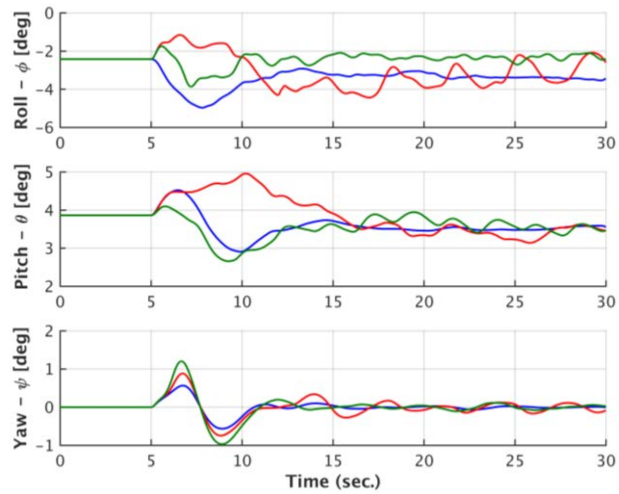
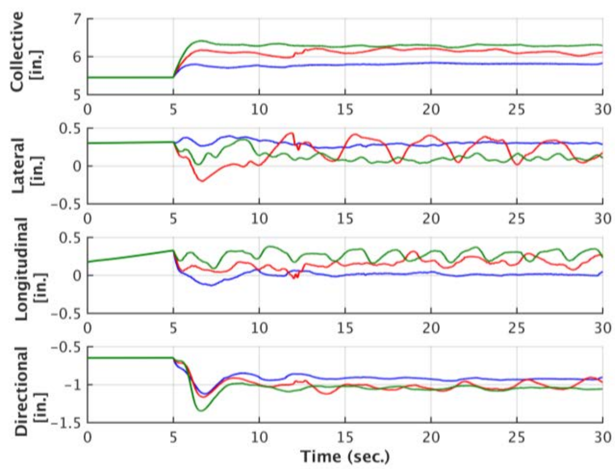


Figure 6. Variations in attitudes of the simulated helicopter hovering IGE, at z=0.5R, z=1R and z=1.5R



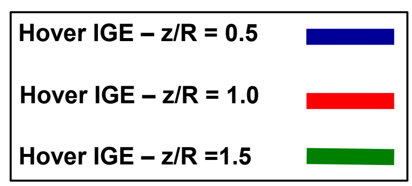


Figure 7. Variations in control inputs of the simulated helicopter hovering IGE, at z=0.5R, z=1R and z=1.5R

Figure 5 to Figure 7 shows the time history change of the response in position, attitude and control inputs of the closed loop helicopter for the fully coupled simulations of hover IGE. After the first 5 seconds of the simulations, there is a transient in the response of the helicopter as it enters free flight. The NLDI controller must then re-trim the helicopter, which it successfully does within several seconds, while the helicopter only drifts a few feet from the original hover location.

The coupled results also show a dynamic behavior for the in-ground-effect (IGE) condition. As can be seen from Fig. 7, there are fluctuations in the attitude response of the helicopter with a period of approximately 5 seconds when it hovers at 1R and 1.5R above the ground. The oscillations result in a small amount of “wobbling” in the aircraft position as well as control responses in reaction to the disturbances. The impact of the fluctuation is much more active in the roll dynamics of the helicopter (possibly because this axis has the lowest inertia). Experimental studies have shown a significant

perturbation to the flow near the rotor blades is caused when the wake of a helicopter rotor interacts with the ground (Ref. 12). Minor oscillations when hovering in ground effect have also been observed by pilots. Especially during the transitional flight, the interaction between the main rotor flow and the ground vortex can have a crucial effect on handling qualities. If these solutions are accurately predicting this phenomenon, it shows the potential of using coupled simulations to analyze ground interaction effects.

Improvements on Flight Dynamics / CFD Coupling Interface

Previously (Ref. 11), data exchanges were performed using file input/output (IO), where data were written to disk during output and read from disk on input. These disk operations are generally very inefficient and system dependent. As speed-improvements are required toward real-time computations, a more efficient data exchange method would be needed. Data exchanges between two independent solvers without file IO is achievable as long as the data exists in memory and is accessible between the solvers. One way of doing this is condensing the GENHEL-PSU code into a library consisting of Application Program Interface (API) functions that need to be called at appropriate times. However, in addition to the complexity of resolving the code to callable routines, many different portions of the code not involving the data exchanges need to be called by the parent CFD solver simultaneously as other CFD tasks by dedicating one processor task to make the API calls.

An alternate method that was eventually chosen requires having the two solvers operate in a Multiple Program Multiple Data (MPMD) Message Passing Interface (MPI) framework. The two solvers are independent executables, which are operated through common MPI execution. In order to enable conversion of these independent solvers to this MPMD framework, the underlying MPI calls to do data exchanges need to be correctly implemented. GENHEL-PSU, due to its fast computational performance, requires no data parallelization and hence remains a serial solver. Therefore, converting GENHEL-PSU into the MPMD MPI framework required the introduction of an MPI front end module, which enables the passage of data between itself and the CFD solver. However, within the GENHEL-PSU portion of the execution, tasks are not parallelized and maintain their serial execution code. A schematic of this MPMD approach is shown in Figure 8. When both solvers are executed using MPMD with N total processors, the global MPI communicator is split so that N-1 processors are assigned for the CFD solver to form the CFD communicator, while 1 process is assigned for GENHEL forming the counterpart GENHEL communicator. A new module representing the GENHEL-PSU's MPI front end handles the sending and receiving of the data streams. Data exchanges are performed by linking the first CFD processor - the "manager" - to the sole GENHEL-PSU processor to form an intercommunicator.

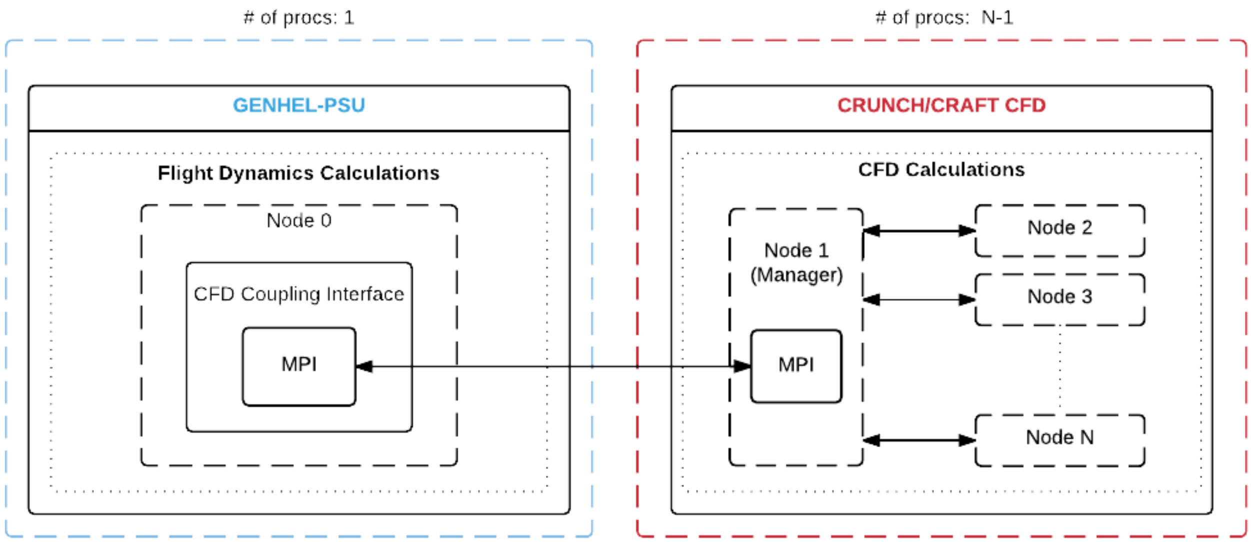


Figure 8 – Schematic of MPMD MPI execution framework

Within the CFD communicator, data received by the "manager" is communicated to the "worker" processors by broadcast operations. The searches are performed in parallel, with host processor and nearest grid point being stored at the end of the search. At the end of the CFD time step, velocity at the nearest grid point for each rotor element is gathered back to the "manager" and then transferred over to GENHEL-PSU.

2. Significance of Results

The comparisons between the CFD flow predictions and the experimental results on rotor outwash are reasonable and provide some confidence in the analysis tool, and we will continue to search for additional validation data. The oscillations seen in the free-flight HIGE simulations are interesting, in that they appear to predict unsteady ground interactions that have been observed in experimental studies and by operational pilots. Simulations will be extended for a helicopter hovering over full/partial ground, sloped ground and near wall; flying in low forward speed and accelerating/decelerating both in and out of ground effect. The new coupling approach using MPMD MPI framework has been successfully implemented on both GENHEL-PSU and CRUNCH/CRAFT codes. Initial results show promising speedups on the calculation times.

3. Plans and upcoming events for next reporting period

- The flight dynamics behavior of the helicopter in IGE condition will be investigated in more details. Simulations will be extended for a helicopter hovering performing different IGE flight tasks such as hovering over partial ground, sloped ground and near wall; flying in low forward speed and accelerating/decelerating both in and out of ground effect.
- We will continue to collaborate with CRAFT Tech to improve the efficiency of the new coupling interface. We were able to run near-realtime piloted simulation. Several optimizations will be done on the computational grid, turbulence models and the coupling interface to enable the real-time piloted simulations. We hope to achieve this within next quarter.

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5. Transitions/Impact

No major transition activities during the reporting period.

6. Collaborations

We had a meeting with CRAFT Tech in late October 2015 to work towards a real-time demo of fully coupled simulations. PSU ported the coupled GENHEL-PSU code and X-Plane graphics interface to CRAFT Tech. CRAFT Tech coupled this code with their more efficient structured grid solvers and implement on their computing cluster. We were able to achieve a near-realtime piloted simulation: GENHEL ran on the cluster head node, coupled to a CRAFT simulation of a simple shedding test case running on all of the compute nodes (256 processors). GENHEL communicated with the joystick controller and X-plane via a network port on the cluster head node. Results will be presented in the Annual Project Review in early November.

7. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

8. Publications

We have submitted an abstract paper, "Towards Real-time Fully Coupled Flight Dynamics and CFD Simulations of the Helicopter / Dynamic Interface", to the next AHS Forum 72 which will be held in May 2016.

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